DESIGN, FABRICATION AND TESTING OF MODEL OF MODIFIED SAVONIUS ROTOR WIND TURBINE

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CERTIFICATE

It is certified that the work contained in the thesis titled DESIGN, FABRICATION AND TESTING OF MODEL OF SAVONIUS ROTOR TYPE WIND TURBINE by MANJITH SATHYAKAN has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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ABSTRACT

Wind turbines are devices which utilise the energy of the wind for practical applications like flour grinding, water pumping and electricity generation. Depending on the orientation wind turbines can be classified as Horizontal axis (HAWT) and vertical axis Wind Turbines. (VAWT)

In this experiment a modified Savonius-type vertical axis wind turbine is considered. The power developed by the wind turbine varies as the cubic of the wind speed. The rotor of the wind turbine consists of 2 end plates, 3 semi circular curved plates and 3 flat plates. A slit has been made on each of the 3 curved plates and a shutter has been designed which is supposed to open when the wind speed exceeds 12 m/s thus stabilising the power.

The rotor dimensions are calculated based on the blockage criteria and NWTF balance data. The shutter opens when the wind speed becomes more than the rated wind speed to stop excess power production. The shutter is connected to the top of the rotor by a wooden connector and flap and hinge arrangement.

For the shutter to open at the design speed the moment equilibrium about the hinge is taken. The wind force lifting moment is balanced by moments due to weight of the shutter and connector.

Two sets of test were done on the model. In the first the shutter of one curved plate is kept unlocked. The flat plate for this is aligned at angles from -40 to 40 deg . with the wind direction. The wind speed is increased steadily from 6 m/s and the speed at which the shutter opens is noted.

In the second all 3 shutters are kept closed. The angle of incidence is varied from 0 deg. to 120 deg. in steps of 10 deg. The wind speed is varied from 8 m/s to 20 m/s and the values of normal force, side force and rolling moment is noted from the strain gauge balance arrangement.

A mounting mechanism for dynamic testing has also been fabricated. But due to non-availability of the horizontal sting mounting system dynamic test has not been done. More details of this are available in chapter 4.

List of Figures

Contents :

INTRODUCTION AND LITERATURE SURVEY

A windmill is a machine which converts the kinetic energy of the wind for useful purposes like water pumping , grain grinding etc. A modern windmill or wind turbine is used for the conversion of kinetic energy of wind for power generation. A modified Savonius rotor which is a VAWT is considered in this experiment. The oldest applications of wind energy were corn grinding by windmills and ship propulsion by sails.

The speed at which the wind turbine starts producing power is called Cut-in speed, normally this is about 3.5 m/s. Power varies with the cubic of wind speed. The speed at which the power is made constant is called rated speed. This is about 11 m/s. The shutter mechanism designed in this experiment is supposed to open at 12 m/s thus reducing the torque and stabilising the power. The power corresponding to this speed is the rated wind power of the turbine. The speed at which the turbine is halted, disengaged or brakes are applied is called Cut-out speed of the turbine. This is about 25 m/s. The maximum wind speed which can be withstood by the turbine is called the survival speed and is about 45-55 m/s. (Fig 1.1)

Instruments used to measure wind speed are called anemometers. The main types of anemometers are

1- Pressure anemometer.

2- Half-cup anemometer.

3- Windmill anemometer.

4- Gust anemometer

5- Hot- wire anemometer.

In this experiment a vertical axis, modified Savonius rotor type wind turbine is considered. The Savonius rotor was invented by the Finnish enginer S.Savonius in 1924. This consists of 2 half cylinders whose axes are offset relative to one another.

The original model was constructed with a ratio of $e/d = 1/3$, e representing the offset of the inside edges and d the diamenter of the two half cylinders that make up the rotor. The machine is primarily a differential drag machine although at certain orientations lift also contributes to torque. This turbine is easy to construct. (Fig.1.2)

The Savonius rotor has been studied extensively by Canadian researchers Neumann and Lek Ak Chai. They studied the performance of the rotor for different values of offset e. The standard Savonius rotor is shown in Figure 1.2.

The ratio of the speed of the tip of the wind turbine to wind speed is called tip speed ratio. The best results of torque and power are obtained for rotors constructed with paramenter $e/d = 1/6$ for which the maximum power coefficient reaches 0.3 For the original Savonius rotor the maximum power coefficient is 0.25. This is achieved when tip speed ratio is between 0.9 and 1.0. The average torque is very high and there is very large variation in torque.

The power coefficient C_p is defined by

$$C_P = \frac{P}{1/2\ \rho\ S\ V^3}$$

Where

P = Power output of turbine

ρ = density of air

S = area of turbine (projected in the wind direction)

V = velocity of air

The torque coefficient is defined by :

$$C_Q = \frac{Q}{1/2\, \rho\, S\, V^2 R}$$

Where

Q = torque output of turbine and R= D/2 is the radius

The Power and torque coefficients are related by :

$C_P = C_Q$* tip speed ratio

The following data have been obtained from reference 1.

$C_{P_{max}} = 0.3$ S = Dh.

$\rho = 1.225$ kg/m^3

$P_{max} = 0.18\, SV^3$

Where

D = diameter of rotor

h = height of rotor

The modified Savonius rotor has been studied extensively by Prof. Nguyen Vinh and data are available in Ref. 1.

The important features of vertical axis wind turbines based on differential drag are

1- No yawing mechanism is needed to orient the turbine with the wind.

2- The modified Savonius Rotor has high starting torque.

3- Cyclic varying gravity stresses found in the cases of horizontal axis wind turbines are absent.

For modified Savonius rotor for any angle of attack there are at least two aerofoils which give positive torque and only one gives the negative torque. Hence this is unidirectional and at no point it produces negative torque as in the case of Savonius. The flat plate directs the airflow towards the cup which adds to the drag. The flat plate acts like a splitter plate, which reduces the drag by narrowing the wake, when moving upwind. So net drag difference gives a huge torque. This has been taken from reference 4 and reference 3.

Reference 3 gives the effect of Splitter plate on the drag of the bluff body attached to it.

Reference 5 gives some perspective on windmills for Indian rural conditions.

CHAPTER 2

THEORY

LIFT AND DRAG TRANSLATORS

2.1 Drag translator :

Consider a cup shaped bluff body moving with a velocity v relative to a wind speed of V.The body moves in a straight line in the direction of the wind.The swept area S is independent of the velocity v. The bluff body has a large wake and hence drag is maximised. This is the simplest arrangement for extracting power. (Fig. 2.1)

Relative velocity = V- v

$D = 0.5 * \rho * (V-v) * (V-v) * S * C_D$

$P = D\,v = 0.5* \rho\ (V-v)^2\ vSC_D$

$P = P\,(v)$

For maximum and minimum values of P

$$\frac{dP}{dv} = 0$$

Maximum power occurs when $v = \dfrac{V}{3}$

Minimum power occurs when v = V.

$$Pmax = \frac{0.5*\rho *C_D*S*4*V*V*V}{27}$$

Power coefficient = C_P

$$C_{P_{max}} = \frac{Pmax}{(0.5*\rho* V*V* V*S)} = \frac{4}{27} C_D$$

For cup shaped bluff body C_D = 1.1-1.2

$$C_{P_{max}} = \frac{4}{27} = 0.14$$

2.2 Lifting translator :

In this case the element moves prependicular to the wind. The work is done by lift as motion is opposed by drag. (Fig 2.2)

V = velocity of wind.

v = velocity of the body.

α = angle between v and V.

c = chord, width (span) = 1

As v increases L and D vary with the relative wind.

$$\text{Cos }\alpha = \frac{V}{\sqrt{(V^2+v^2)}} \qquad \text{Sin }\alpha = \frac{v}{\sqrt{(V^2+v^2)}}$$

$$P = 0.5*\rho*V*V*C*1*(C_L \text{Cos }\alpha - C_D \text{ Sin }\alpha)*v$$

$$\text{Substitute } E = \frac{L}{D} = \text{efficiency of aerofoil} = \frac{C_L}{C_D}$$

$$R = \frac{v}{V} = \text{Speed ratio}$$

$$P = 0.5*\rho*C*(1-R/E)*R*(1+R*R)$$

$$C_P = \frac{P}{(0.5*\rho*V*V*V*C)} = C_L*(1-R/E)*R*(1+R^2)$$

$$C_P = C_P(R, C_L, E)$$

$$\frac{dC_P}{dr} = 0$$

$R = (E+(E*E-8)/4$ $\qquad$ E = 30 -40 for aerofoil.

When E>> 8, R~E/2

$$C_{P_{max}} = C_L*(4+E*E)/4 \sim C_L*E/4$$

2.3 Comparison of lift and drag translators :

1. Lift translator can operate at V>v drag translator cannot.
2. For the sake of comparison take $C_L = C_D = 1$.

For a lift translator $C_{P_{max}} = \frac{E}{4}$

For a drag translator $C_{P_{max}} = \frac{4}{27}$

$$\frac{(P_{max}/\text{lift})}{(P_{max}/\text{drag})} = (27/16)^{*}\ E.$$

Since E > 40, the above ratio is 60.

Drag torque > Lift torque.

The lift translator is difficult to design, maintain and costly.

2.4 Rankine-Froude Actuator Disc Theory:

The rotor is replaced by an actuator disc through which the static pressure decreases discontinuously. The following assumptions are made. (Fig 2.3) (Ref 2)

1. Steady, homogeneous wind.
2. No obstruction to wind flow either upstream or downstream.
3. The flow velocity at disc is uniform.
4. Incompressible fluid.
5. No rotation of flow produced by disc.

p_0 = ambient static pressure far ahead of the windstream.

S = cross-sectional area of control volume.

v = decrease in velocity of wind due to rotating disc.

V_0 = wind velocity far ahead of the disc.

u = $V_o - v$ = Velocity immediately after disc.

u_1 = velocity far downstream of disc. The pressure returns to p_0.

A = area of rotor disc.

ρ = density of air

T = momentum lost by fluid = thrust exerted by rotor against flow.

From continuity equation

$$V_o A_o = uA = u_1 A_1.$$

let DQ = net flow out of the sides of the control volume shown.

$$DQ = V_o * [(S-A_0)-(S-A_1)] = V_o * (A_1 - A_o)$$

Writing the momentum theorem for the cylindrical control volume

$$\rho V_o^2 S - T = \rho V_o^2 (S-A_1) + \rho u_1^2 A_1 + \rho DQ V_o.$$

Substituting for DQ and $V_o A_o = u_1 A_1$.

$$T = \rho * A_1 * u_1 * (V_o - u_1)$$

Physically an actuator disc can be approximated by a rotor with a large number of very thin, dragless blades rotating with a tip speed ratio higher than 1.

Applying the Bernoulli equation between section 0 and

section 3 and between section 2

$$1/2\ \rho\ V_0^{\ 2}+p_o= 1/2\ \rho u^2+p_3,$$

$$1/2\ \rho u^2+p_2 = 1/2\ \rho u_1^{\ 2}+p_o.$$

The thrust on the rotor is given by

$$T=A(p_3-p_2)$$

Substituting for p_3-p_2 from above

$$T= \rho A(V_o^{\ 2}-u_1^{\ 2})/2$$

Equating the above equations and using $Au=A_1u_1$

$$u=(V_o+u_1)/2$$

This implies that the velocity at the disc is the average of the upstream and downstream velocities. Defining an axial interference parameter a

a = fractional decrease of wind velocity across rotor disc.

$$a= v/V_o$$

$$u= V_o(1-a)$$

$$u_1=V_o(1-2a)$$

The energy extracted by the rotor per unit time is

$$P=1/2\ \rho V_o^{\ 2}Au-1/2\ \rho u_1^{\ 2}Au$$

$$= 1/2\ \rho\ Au(V_o^{\ 2}-u_1^{\ 2})$$

$$= 1/2\ \rho Au(V_o-u_1)(V_o-u_i)$$

substituting for u we find

$$P = 1/2\ \rho\ AV_o^{\ 3}4a(1-a)^2$$

Defining power coefficient $C_p = P/(0.5\ \rho\ A\ V_o^3)$

$C_p = 4a\ (1-a)^2$

C_p^{max} occurs when a=1/3

$C_p^{max} = 0.593$

We also find that

$u=(2/3)V_o$

$u1 = (1/3)V_o$

$T = \rho A(V_o^2 - u_1^2)/2$

taking $u_1 = V_o(1-2a)$

$T = 1/2\ \rho\ V_o^2 A4a(1-a)] = qA4a(1-a)]$

q = dynamic pressure.

Thrust coefficient = $C_T = T/qA$

$C_T = 4a\ (1-a)$

Torque coefficient = $C_Q = Q/(0.5V_o^2 Sr)$

S = entire area of turbine.

r = maximum radius.

Tip speed ratio = TSR

= (Velocity of tip of wind turbine/Velocity of free stream)

The power and torque coefficients are related by

$C_p = C_Q$*TSR.

2.5 Qualitative Theory of modified Savonius rotor :

The modified savonius rotor is a primarily differential drag rotor. The drag on the reverse or concave part of the cup is greater than the drag on the obverse or convex part. This difference in drag gives a torque.When downstream of cup, the flat plate acts as a splitter plate and reduces drag (Ref. 3). When it is upstream the flat plate deflects flow onto the cup. The flat plate receives lift at certain angles and adds to the torque. At any orientation there are atleast two aerofoils giving positive torque. The torque is always unidirectional unlike the original savonius rotor.

No quantitative theory is available for explaining the performance of modified savonius rotor. Experimental investigation is the only way to study the performance of this rotor.

CHAPTER 3

DESIGN

3.1 Design Purpose :

The modified savonius rotor consists of 2 top and bottom plates, 3 pairs of half-circle and flat plates. The dimension have been chosen considering the blockage criteria and weight of model. The length of the flat plate is 40 percent of the diameter of the top and bottom plates. (Fig 3.1)

The purpose of the experiment is to stabilise the power of the wind turbine at 12 m/s. A slit is made on the curved plates and a shutter mechanism has been designed which opens when the wind speed exceeds 12 m/s, thus preventing the drag from increasing and stabilising the power. The model is made from aluminium.

The shutter is made of 18 gage mild steel. A wooden connector is rivetted to this. The wooden connector is connected to the top plate by a flap and hinge arrangement. The shutter is free to open when the wind speed becomes more than 12 m/s. The moment equilibrium about the hinge is considered while designing the shutter. The wind force lifting moment is balanced by moments due to weight of shutter, connector and the flap, about the hinge. (Fig. 3.2)

3.2 Material Estimation :

The following components are needed for the construction of the rotor arrangement.

1. Top and bottom plates.

   Two aluminium circular sheets are needed.

   diameter = 70 cm.

   thickness = 3 mm.

   Due to margin for marking the circle on the aluminium sheet the diameter has been reduced to 68 cm.

2. Flat plates.

   Three aluminium plates are needed.

   length = 28 cm. height = 50 cm.

   thickness = 3 mm.

3. Curved plates.

   Three aluminium plates are needed.

   circumference = 3.14*14 cm = breadth = 43.96 cm.

   height = 50 cm.

   thickness = 3 mm.

4. Angles

For connecting the flat plates and curved plates to the top and bottom plates 42 L-shaped angles of dimensions 25 mm. x 25 mm. x 15 mm. and thickness 1.25 mm are needed.

5. Wooden connector.

Three wooden connectors are needed.

length = 18 cm.

breadth = 4 cm

thickness = 0.7 cm

6. Flaps and hinges.

Three pairs of flaps and hinges are needed.

7. Shutters.

Three shutters have been fabricated from 18 gauge mild steel of thickness 1.25 mm. Material has been removed from the tip of the shutters for smooth movement of the shutters through the slit.

3.2 Calculation of rotor dimensions :

The rotor consists of 3 blades each made up of a half circle combined with a flat plate. The quantities L, D, d are shown in the figure 3.1.

D = Diameter of rotor

d = diameter of 3 curved plates.

L = length of 3 flat plates.

H = height of rotor.

From figure 3.3

$$L*L = (D/2*D/2) - (D/2-d+d/2)* (D/2-d+d/2)$$

$$L*L = (D*d/2)- (d/2*d/2)$$

It has been found that maximum power for the same wind speed is obtained when $L = d$.

Substituting $L = d$ in the above equation $d = 0.4D$.

$$\text{Area } A1 = d*H$$

$$\text{Area } A2 = (d/2+d*\cos 30)*H=H/2* (1+\sqrt{3})*d$$

$$\text{Projected area normal to tunnel} = A = A1 + A2$$

$$A = d*H+H*d/2*(1+\sqrt{3})$$

$$A = (dH/2)\,(3+\sqrt{3})/\,100\ m^2$$

Area of test section in NWTF = 2.2 m *3m = 6.6 m^2

Various values of D,d,H,L are considered and the precentage blockages calculated in the table below.

Sl No.	D(cm)	d(cm)	H (cm)	L(cm)	A(m*m)	% blockage
1	90	36	70	36	0.596	9.034
2	90	36	65	36	0.554	8.389
3	85	34	70	34	0.563	8.532
4	85	34	65	34	0.523	7.923
5	80	32	60	32	0.454	6.883
6	80	32	55	30	0.416	6.309
7	75	30	55	30	0.390	5.915
8	75	30	50	30	0.355	5.377
9	70	28	50	28	0.331	5.019

The rotor dimensions are selected based on the criteria that the model should not block more than 5% of the tunnel area. Hence the dimensions chosen are

$D = 70cm$, $H = 50$ cm, $d = 0.4 * D = 28cm$

This gives $A = 0.331 m*m$

3.3 Design of shutter :

The shutter is designed to open at a wind speed of 12 m/s. For this the moment equilibrium about the hinge is taken. The wind force lifting moment is balanced by the moments due to weight of shutter, wooden connector and flap. (ref fig 3.2

F_W = Wind force on shutter

$= 0.5*C_D* \rho * V^2 * A_S$, A_S = area of slit.

$= 0.5 *1 *1.225 *12 *12 * 0.35 *0.01$

$= 0.3087$ N

Wind force lifting moment about hinge

$= 0.3087 *0.25 \quad = 0.07718$ Nm

The centroids of the shutter, connector and flap have been calculated and their distance from the hinge has been shown in fig. 3.2.3. (ref 3.2.2 also).

Weight of connector = 20 g = 0.02 kg

Weihgt of flap = 34 g = 0.034 kg

Let weight of shutter = W_S.g

Distance of centroid of shutter from hinge = 12.62 cm

Distance of centroid of connector from hinge = 5.83 cm

Distance of centroid of flap from hinge = - 0.63 cm

Taking moment equilibrium,

$$(W_S * 0.126 + 0.02* 0.058 -0.034 * 0.0063) * 9.8 = 0.07718$$

This gives $W_S = 55$ g $= 0.055$ kg

This weight of shutter is to be achieved by drilling lightening holes in the shutter.

CHAPTER 4:

FABRICATION,EXPERIMENTAL SETUP AND TEST PROCEDURE.

4.1 Fabrication:

The model to be tested has 2 top and bottom plates,3 pairs of curved and flat plates all made of aluminium. They are connected in the desired shape by angles made of mild steel. The shutters are made of 18gage mild steel. The 3 diagonal connectors are connected with flaps and hinges to the top plate.

In addition to the above for dynamic testing a rotating mechanism was fabricated. This consisted of a 12mm diameter stainless steel rod mounted on 2 bearings.The bearings are housed in a mild steel cylinder of inner diameter 32 mm and outer diameter 60mm.A steel disc of outer diameter 100mm and inner diameter 60mm is force fitted on to this cylinder. Two steel rods have been fabricated on which 6 rubber pieces have been mounted to apply braking torque when required.This is supposed to be welded to the steel disc. This mechanism is connected to the turbine by 2 aluminium flanges.

(Fig 4.2)

4.2 Experimental Setup :

A dummy balance arrangement was done before the actual experiment. Before the experiment the bottom plate of the model was connected to 2 supporting plates by means of suitably placed nuts and bolts. A pre-fabricated central rod is connected to the two plates by means of a key arrangement. This is connected to an adapter by a similar key arrangement. The adapter is connected to the dummy balance provided by means of a screw. (Fig. 4.1)

For the experiment the model was mounted on top of 2 supporting plates of different diameters each of thickness 1 cm. These 2 plates are attached to the bottom turbine plate by suitably placed nuts and bolts. A central rod is attached to the second supporting plate by a key arrangement. This rod is connected to an adapter by a similar key mechanism.The adapter is connected to the balance by a pre-designed mechanism. The balance is placed on top of a second adapter by means of suitably placed screws. This arrangement is attached to the floor of the test section. The strain gauge balance is highly sensitive. The output from the balance can be read in the pre-designed software in NWTF.

4.3 Initialisation :

Before mounting the model it was checked that the weight of the model did not exceed the specified limit for the balance. The weight of the model is 15.75 kg and that of the supporting plates and the central rod weight about 2.5 kg.

4.4 Check for rolling moment :

The productive torque of the turbine model appears as the rolling moment for the balance. It has to be checked that the maximum rolling moment on the model falls within the range of the balance.

C_D for a half cylinder when air is incident on the concave face = 2.3 (ref 1)

C_D for a half cylinder when air is incident on the convex face = 1.2

assume maximum C_D of the total system at any orientation = 3.5

Taking maximum wind speed = 23 m/s.

Corresponding drag = C_D $1/2\,\rho V^2 S$

$= C_D * 0.5 * 1.225 * 23 * 23 * 0.5 * 0.28$

= 158.77 N

Assuming wind force causing rolling acts at the centre of the curved plates.

moment arm = 0.21 m

Maximum rolling moment = 158.77*0.21

= 33.34 Nm = 3.39 kgfm

This is within the permissible range for the balance.

4.5 Check for pitching moment :

It has to be checked that the maximum pitching moment on the model does not exceed the maximum pitching moment capacity of the balance.

Drag on the model considering it a solid rectangular flat plate of same projected area and assuming C_D = 1.2 (ref 1)

Drag = 1.2*0.5*1.225*23*23*0.5*0.68

= 132.1971 N

Distance from centre of model to centre of the balance = 71.45 cm

Maximum pitching moment due to model = 132.1971*0.7145 = 94.45 Nm

Maximum pitching moment capacity of the balance = 15.6 kgfm

= 153.036 Nm

This condition is also satisfied.

4.6 Test procedure :

The model was mounted on the NWTF test section. Two sets of test were conducted. The cross-sectional area of the tunnel is 2.2 m * 3 m. The model is mountd on top two supporting plates. The arrangement is as shown in the photograph. (Fig. 4.6, 4.7, 4.4, 4.5)

4.7 Test 1 :

1. In this set of experiment the shutter of one of the curved plates was not locked while the other two remained locked.

2. The flat plate corresponding to the curved plate with unlocked shutter was oriented at 20 deg to the wind direction in order to obtain full blast of the wind on the shutter. (Fig 4.3)

3. The wind speed is varied from 8 m/s to 20 m/s and the amount of deflection of the shutter is noted.

4. The same procedure is repeated with the flat plate corresponding to the unlocked shutter oriented at 40 deg, 20 deg, 0 deg, -40 deg, -20 deg.

5. The normal force, side force and rolling moment are noted from the strain gauge balance arrangement. The calibrated circuit arrangement and software are available at NWTF.

6. The temperature and pressure inside the test section are also noted.

4.8 Test 2 :

1. In the setup all 3 shutters are kept locked.

2. The flat plate is held at 0 deg to the wind direction. This alignment varies with the balance axis by 31 deg. (Fig 4.3)

3. The orientation of the balance axis with the 0 deg. wind is noted.

4. the wind speed is varied from 8 m/s to 20 m/s at suitable intervals and the angle of attack is varied from 0 deg to 120 deg. in steps of 10 deg. Angles greater than 120 deg are not considered since the flow pattern repeats after every 120 deg.

5. The corresponding values of rolling moment,normal force and side force are noted down from the strain gauge balance arrangement.

6. The actual values of the side force and normal force, Lift and Drag are calculated by knowing the difference in angle between the axis of the strain gauge balance arrangement and 0 deg wind direction by applying suitable transformation.

CHAPTER 5

RESULTS

5.1 Test 1 :

The amount of opening of the shutter with variation in windspeed is noted. The experiment was started at 6 m/s. The shutter remained closed at 6 m s and 8 m/s The amount of opening of the shutter with variation in wind speed and angle of attack is shown below .

Wind speed (m/s)	Angle of attack (deg.)				
	-40	-20	0	20	40
10	closed	closed	closed	closed	closed
12	closed	closed	closed	closed	closed
14	open	open	open	open	closed
16	1.5"	1.25"	1"	1.25"	0.75"
18	2"	2"	2"	2"	1.5"

Maximum amount of tape opening corresponds to 2 inches.

Atmospheric pressure = 29.63 inches of Hg.

Atmospheric temperature = 19^0C

The rolling moment at zero angle of attack for various wind speeds is shown below.

Wind speed (m/s)	6	8	10	12	14	16	18
Rolling moment (kgfm)	0.0661	0.1137	0.1711	0.2463	0.3331	0.4294	0.5366

5.2 Test 2 :

The shutter on all 3 curved plates are kept locked. The wind speed is varied from 8 m/s to 17 m s in steps of 3 m/s. The angle of attack is varied from 0 deg. to 120 deg. in steps of 10 deg. The values of normal force, side force and rolling moment are obtained from the strain gauge balance arrangement. The angle made by the axis of the balance and wind direction is noted. Knowing this, the lift and drag are calculated and plotted against the angle of attack. The balance axis is at an angle of 31 deg. from wind direction at zero angle of attack. (ref. fig 5.6) The sign convention for measuring angle of attack is given in fig. 4.3

5.3 Conclusion :

All graphs of lift vs. angle of attack. (fig. 5.1) are similar. The lift is negative at 40 deg. This is because the flat plate of the second pair of aerofoil produces large negative lift. The lift is maximum at 70 deg. In this position the flat plate of the 3rd pair of aerofoils directs the flow onto the curved plate producing large lift in the positive direction.

All graphs of drag vs. angle of attack (fig. 5.2) are similar. All graphs of rolling moment vs. angle of attack (fig 5.3) are also similar. The plot of rolling moment at zero angle of attack vs. wind speed is also shown (fig. 5.4)

The shutter opens between 12 m/s and 14 m/s. The plot of rolling moment is extrapolated from 12 m/s and this is above the experimental curve for angle of attack 0 deg. and -20 deg. and this shows that some rolling moment and hence power has been cut back when the shutter opens. (fig 5.5).

However for 20 deg. and 40 deg. it seems rolling moment is either improving or remaining the same. This is a feature which needs to be further investigated.

Test 2 :

1 kgf = 9.81 N

Wind Velocity (V) (m/s)	Angle of attack (deg.)	Normal force (NF) (kgf)	Side force (SF) (kgf)	Rolling moment (kgf m)	Lift (kgf)	Drag (kgf)
8.00	0	+1.8830	0.2803	-0.1206	-0.7295	1 7583
8.06	10	+1.40723	0.89607	-0.0495	-0.2469	1.6499
8.10	20	+0.9017	1.2416	-0.0390	0.0806	1.5324
8.18	30	+0.6352	1.27122	-0.329	0.0607	1.4198
8.14	40	+0.7066	0.9896	-0.0226	-0.3459	1.1657
8.14	50	+0.3798	1.0618	-0.0905	-0.2089	1.1081
8.10	60	-0.3631	1.7080	-0.2890	0.3332	1.7141
8.02	70	-0.8703	1.8403	-0.3339	0.5031	1.9725
8.10	80	-0.9889	1.8302	-0.3770	0.2674	2 0631
8.06	90	-1.2782	1.8236	-0.3241	0.1564	2.2214
8.10	100	-1.3857	1.8673	-0.2549	-0.1793	2.3813
8.02	110	-1.46978	1.87781	-0.18028	-0.5344	2.3239
8.10	120	-1.6665	1.5887	-0.1171	-0.5815	2 2278
11.00	0	+3.4735	0.4044	-0.2238	-1.4424	3 1856
11.00	10	+2.8085	1.3139	-0.1348	-0.8508	2 9816
11.03	20	+1.6075	2.2701	-0.0702	0.1793	2.7758
11.06	30	+1.1411	2.3373	-0.0577	0.1351	2.5975
11.12	40	+1.2874	1.8087	-0.04176	-0.6284	2.1293
11.12	50	+0.5949	1.9208	-0.1790	-0.2871	1 9902
11.12	60	-0.7577	3.1166	-0.5305	0.7032	3.1293
11.03	70	-1.3881	3.3348	-0.5501	0.7263	3.5384
11.09	80	-1.8536	3.3836	-0.6929	0.5179	3.8231
11.06	90	-2.2707	3.3487	-0.6064	0.2217	4.0399
10.97	100	-2.4390	3.4418	-0.4709	-0.4173	4.1977
10.94	110	-2.7846	3.4557	-0.3441	0.9332	4.3388
10.91	120	-2.9900	2.9566	-0.2225	-1.1363	4.0485
13.99	0	+5.6166	0.8199	-0.3701	-2.1902	5.2365

Wind Velocity (V)	Angle of attack	Normal force (NF) (kgf)	Side force (SF) (kgf)	Rolling moment (kgfm)	Lift (kgf)	Drag (kgf)
14.08	10	+4.2618	2.5862	-0.1564	-0.8441	4.9131
14 12	20	+2.7309	3.7726	-0 1164	0.2578	4.6504
14 15	30	+1.8871	3.8468	-0.0987	0.2145	4.2794
14.15	40	+2.0229	3.0208	-0.0733	-0.9292	3.5148
14.24	50	+0.9232	3.2415	-0.3139	-0.4047	3.3460
14.13	60	-1.2952	5.0799	-0.8605	1.2064	5.1018
14.01	70	-2.4871	5.5513	0.9876	1.3821	5.9239
14.11	80	-3.0255	5.5269	-1.1293	0.8439	6.2441
14.08	90	-3.7424	5.4644	-0.9899	0.3935	6.6113
13.99	100	-3.9849	5.6570	-0.7639	-0.7039	6 8837
13.97	110	-4.5401	5.5925	-0.5463	-1.4889	7.0477
14.01	120	-4.7836	4.9677	-0.3614	-2.0257	6 5922
17.00	0	+8.2789	1.1802	-0.5367	-3.2523	7.7042
17.06	10	+6.7739	3.1014	-0.3063	-2.1034	7.1470
17.15	20	+3.9451	5.5256	-0.1712	0.4116	6.7770
17.21	30	+2.7876	5.6078	-0.1450	0.2807	6.2562
17.19	40	+3.1125	4.3739	-0.1079	-1.5189	5.1489
17.04	50	+1.3011	4.8496	-0.4919	-0.5265	4 9934
17.08	60	-1.8259	7 4694	-1.2650	1.6953	7.5001
17.04	70	-3.6146	8.1394	-1.4595	1.9953	8.6799
17.04	80	-4.4225	8.1137	-1.6742	1.2211	9.1597
17.02	90	-5.4819	8.0606	-1.4754	0.5474	9.7326
17.04	100	-5.9211	8.3915	-1.1488	-1.0366	10.2177
17.04	110	-6.7408	7.7488	-0.8284	-1.7798	10.1150
1704	120	-7.4616	6.2122	-0.5081	-1.8159	9.5377

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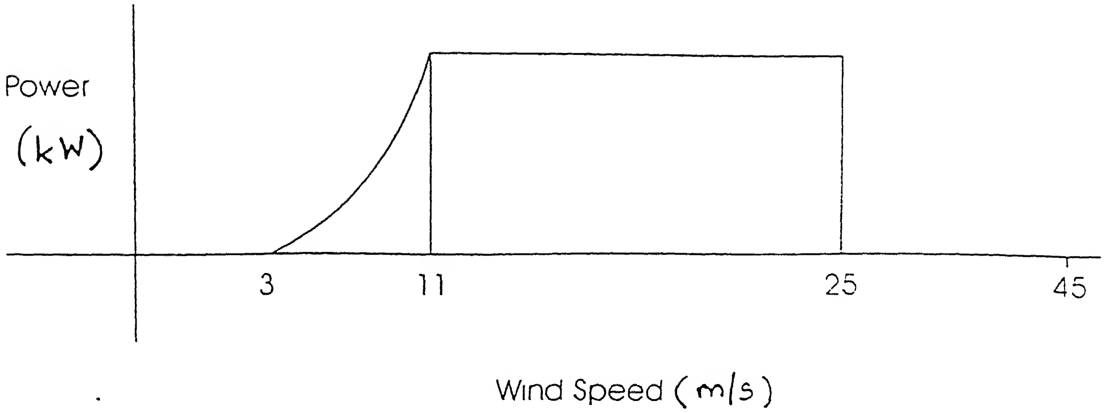

Fig. 1.1 Power vs Wind Speed curve -

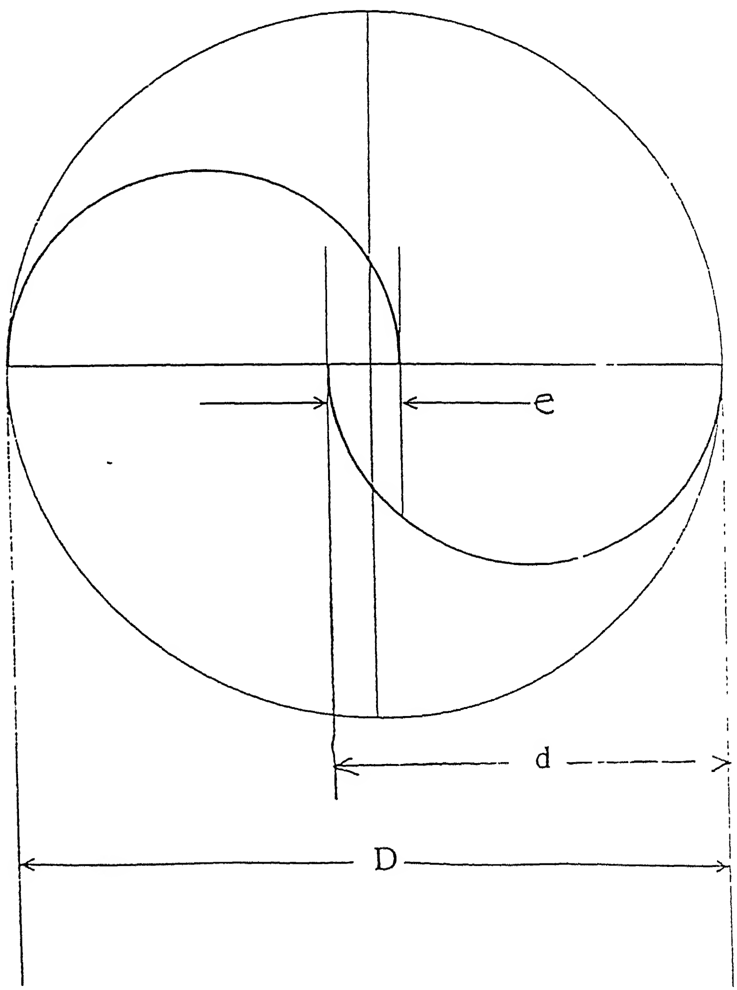

Fig. 1.2 Original Savonius rotor -

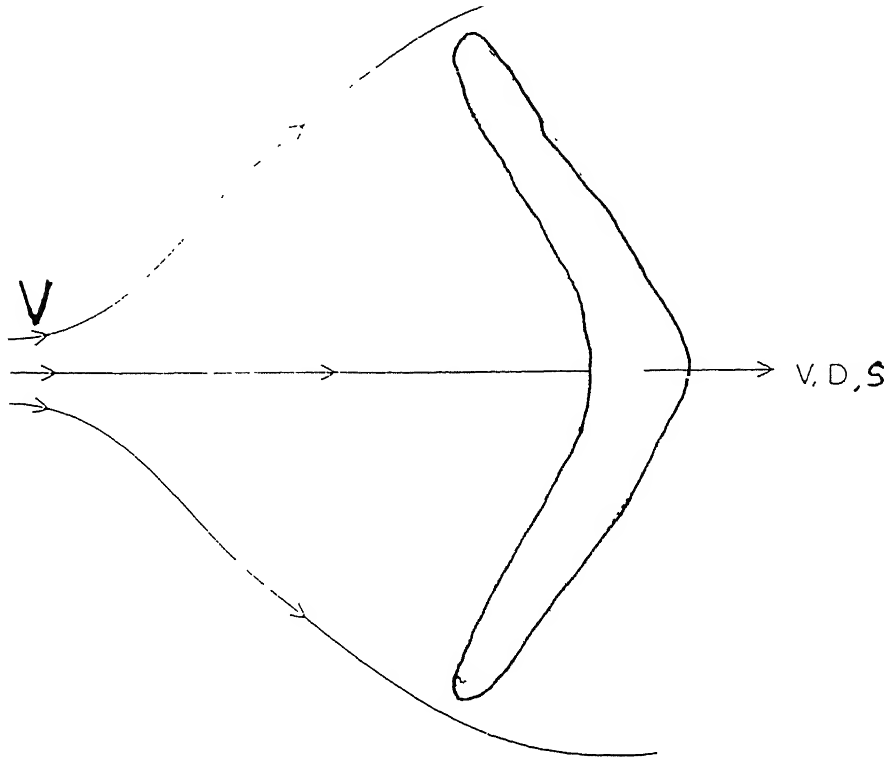

Fig. 2.1 Drag Translator -

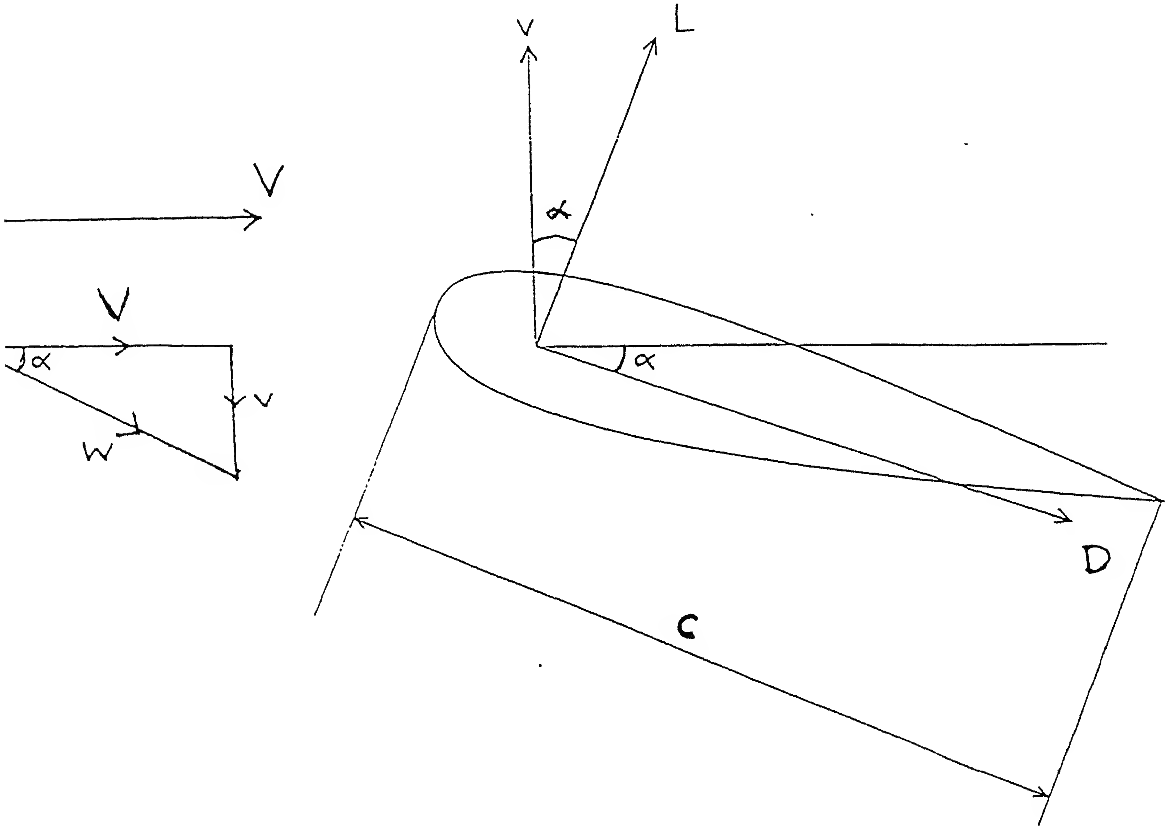

Fig. 2.2 Lift Translator -

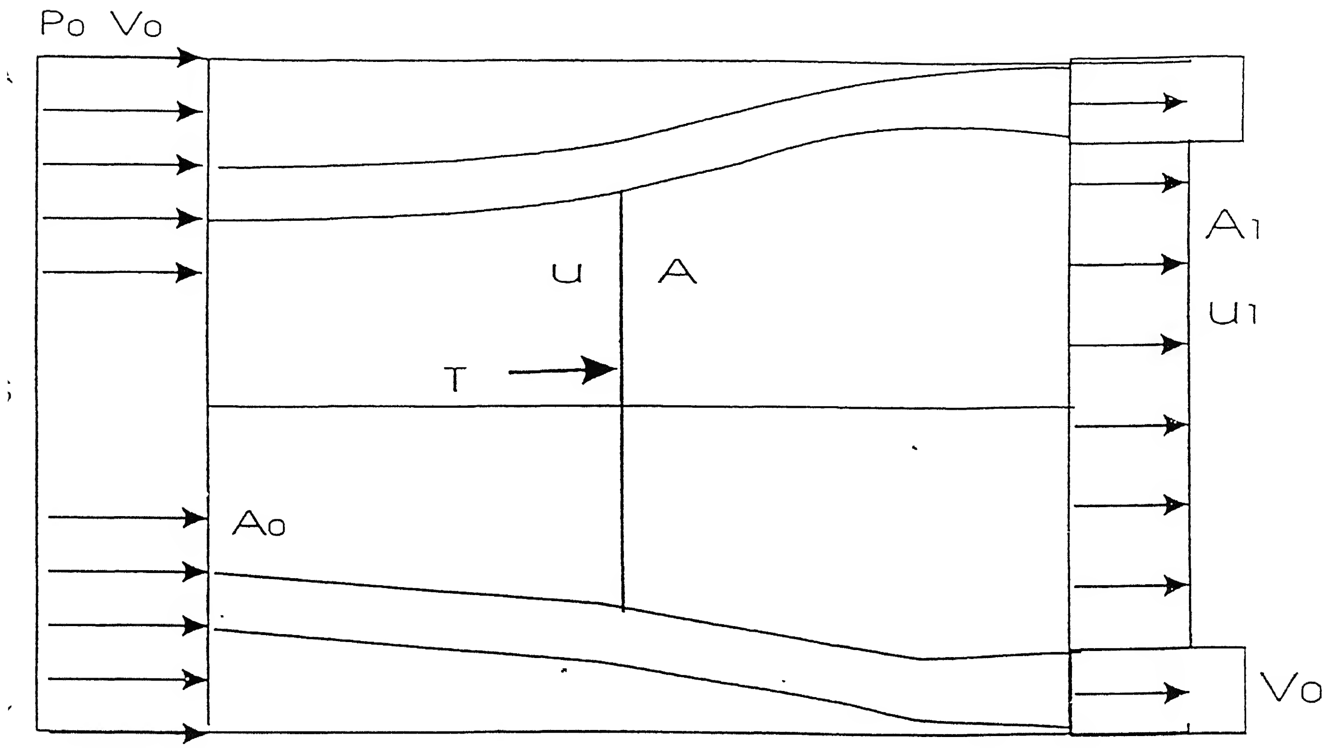

Fig. 2.3 Flow pattern accross Actuator Disc -

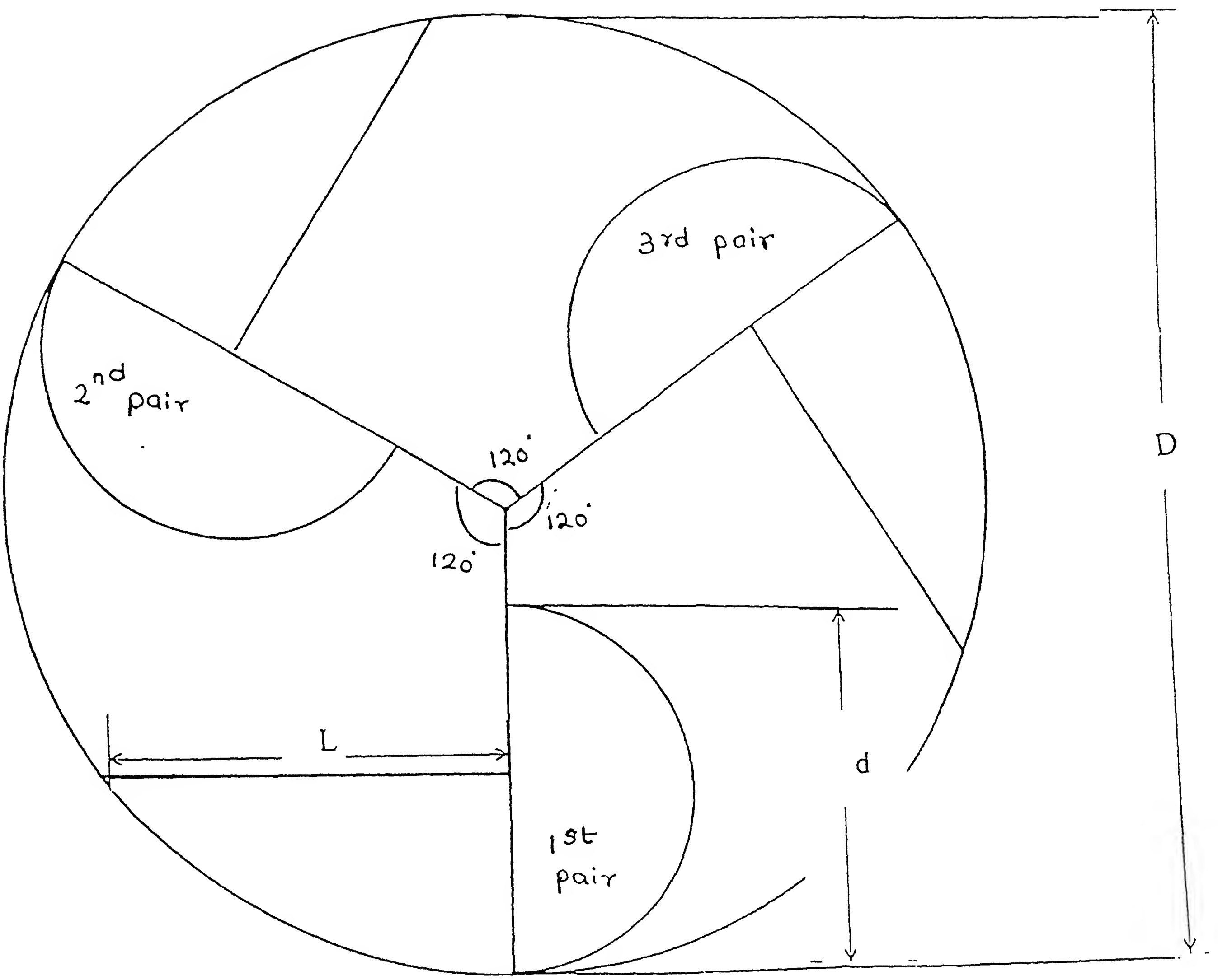

Fig. 3.1 Modified Savonius rotor -

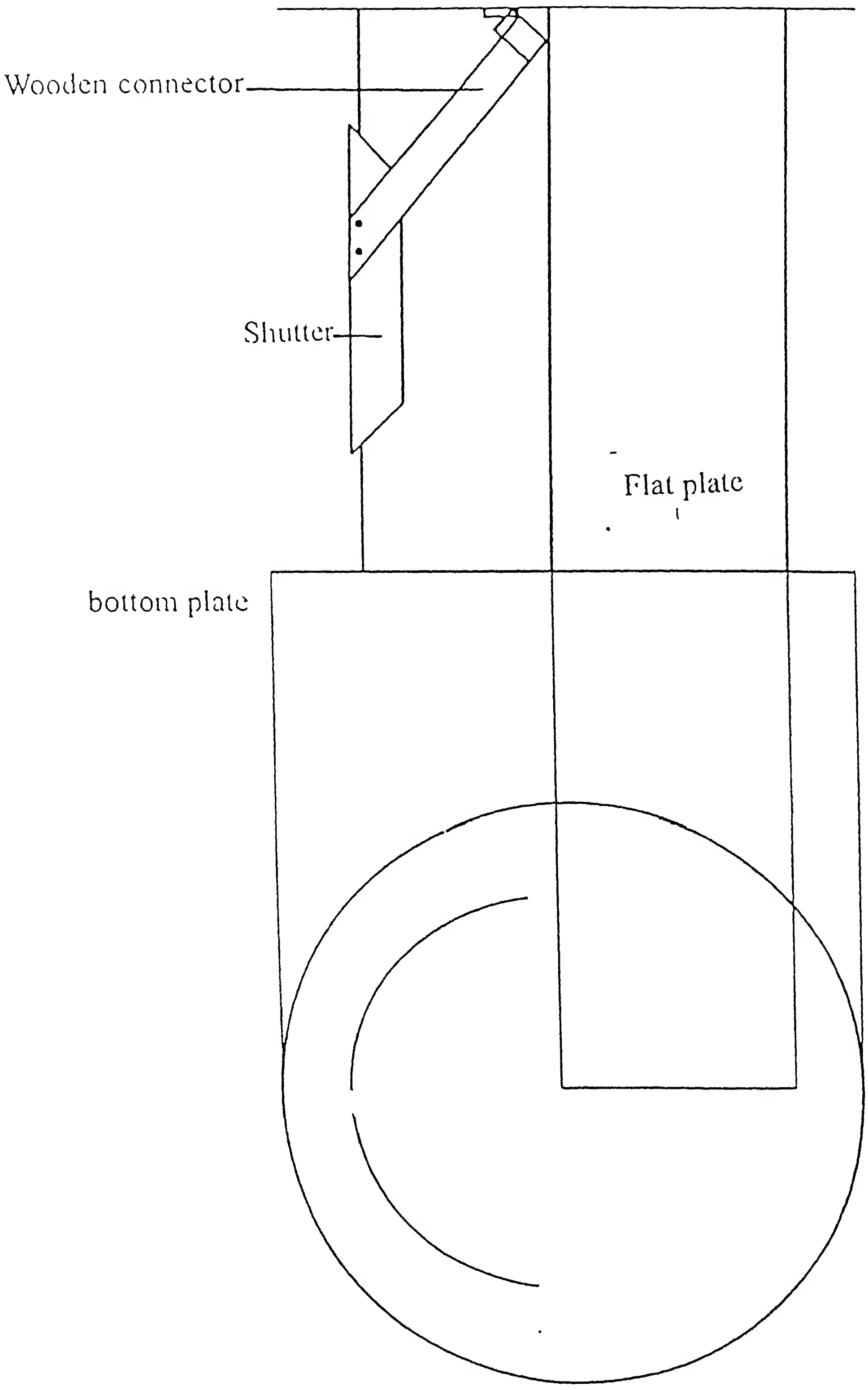

Fig 3.2.1 Shutter arrangement scheme

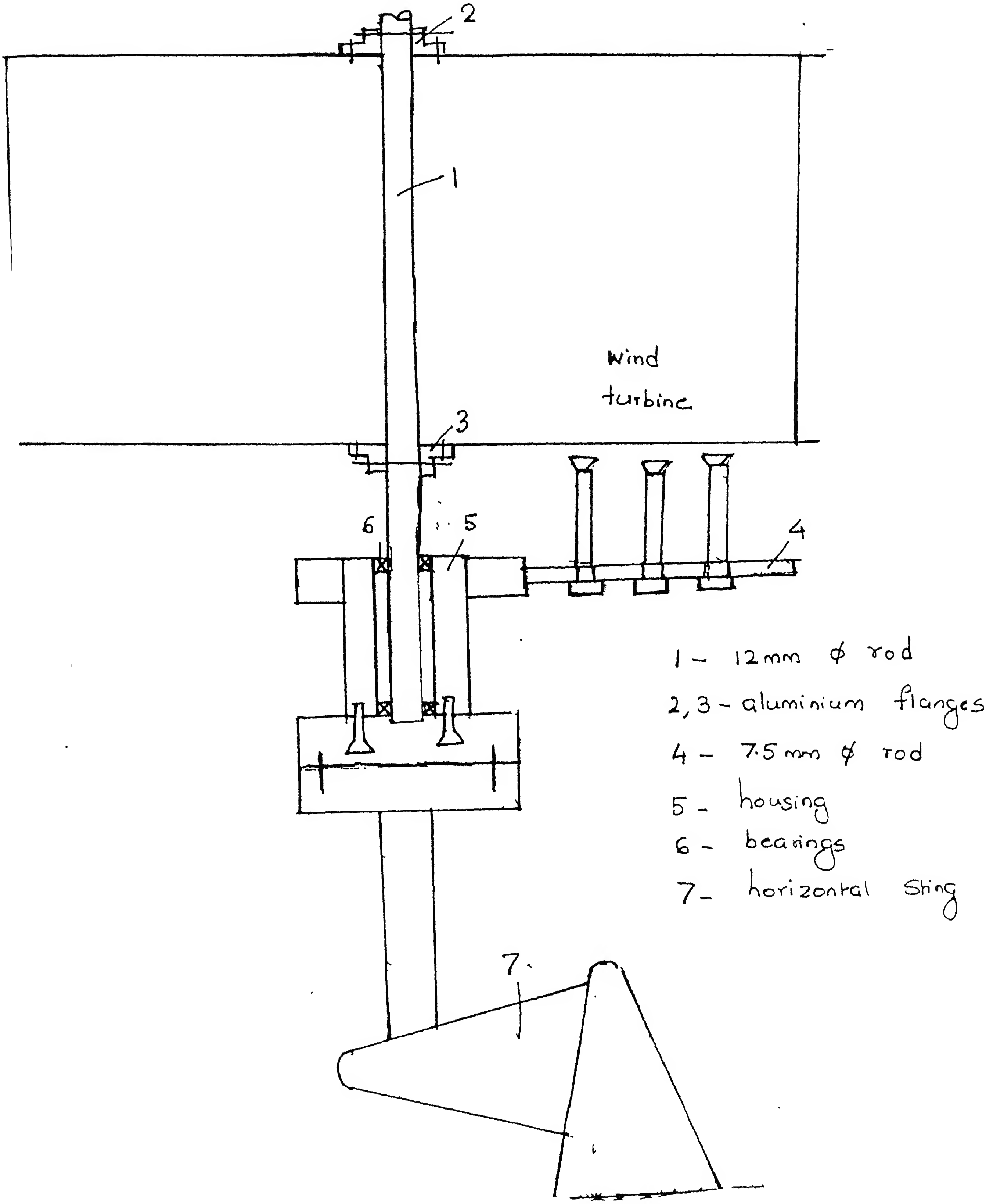

Fig. 4.2 Model mounting mechanism for dynamic testing

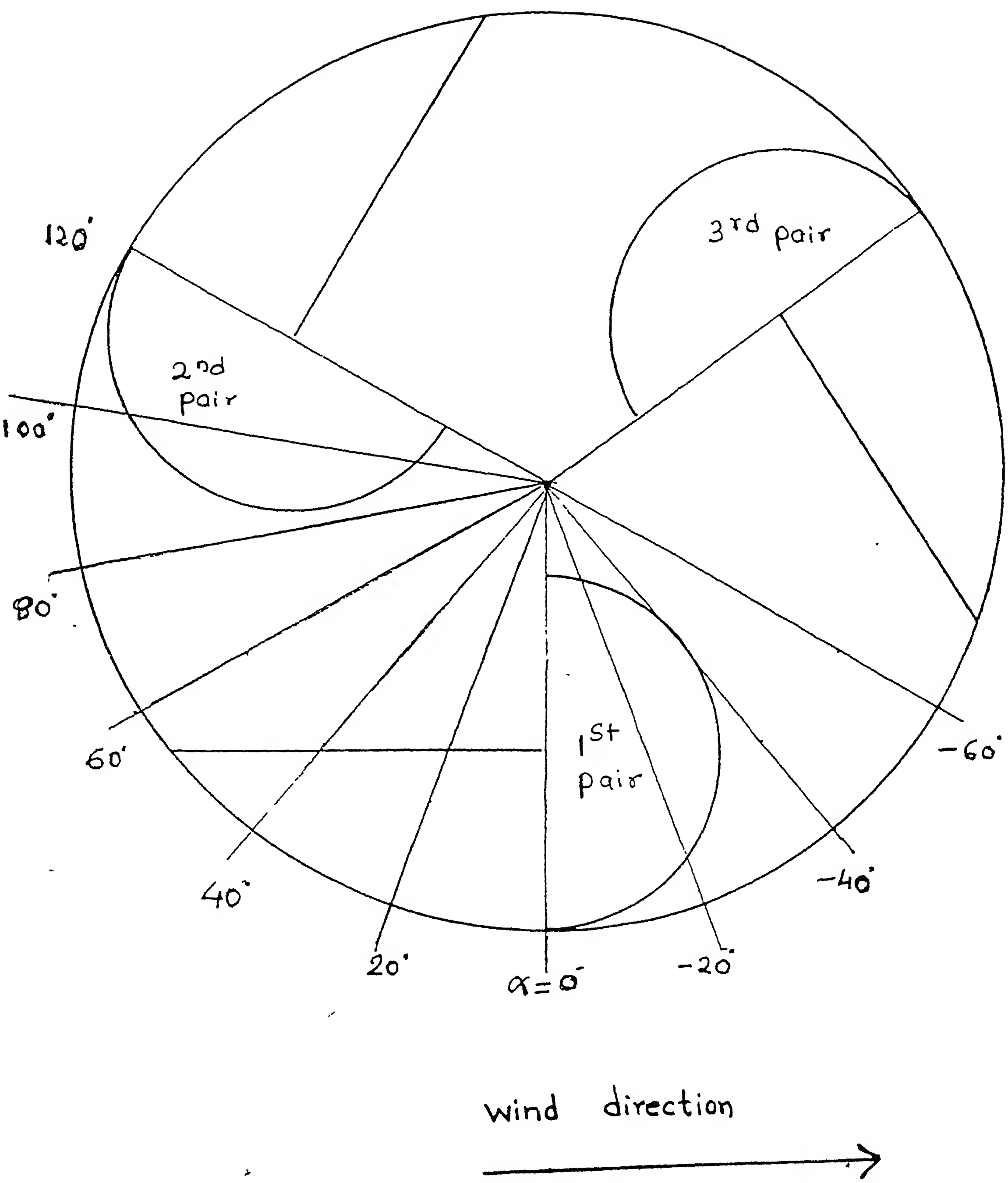

Fig. 4.3 Sign convention for angle measurement

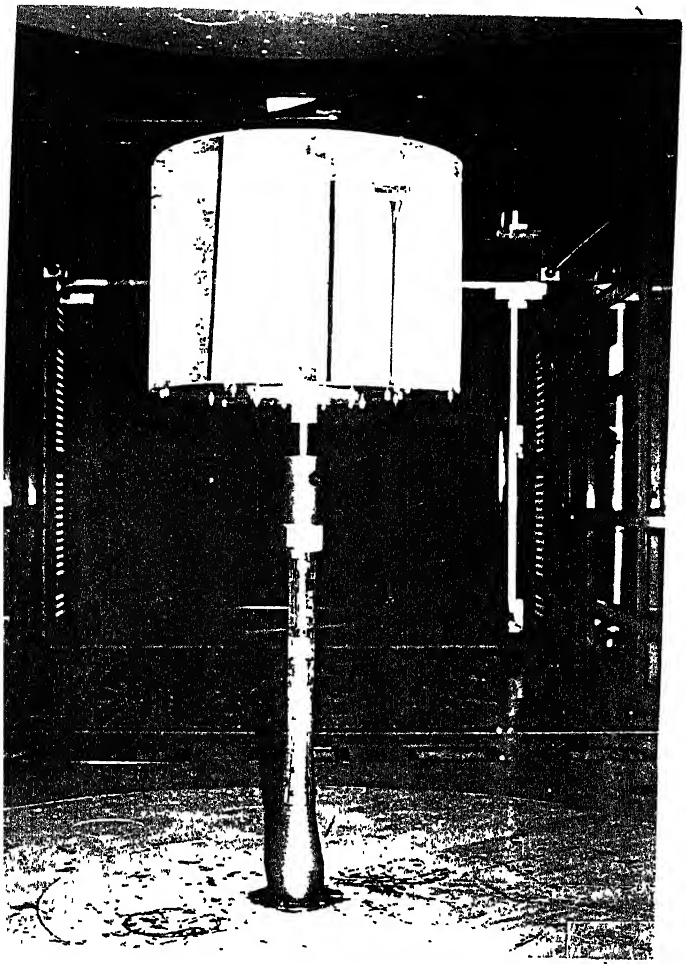

Fig. 4.4 Downstream view of model ·

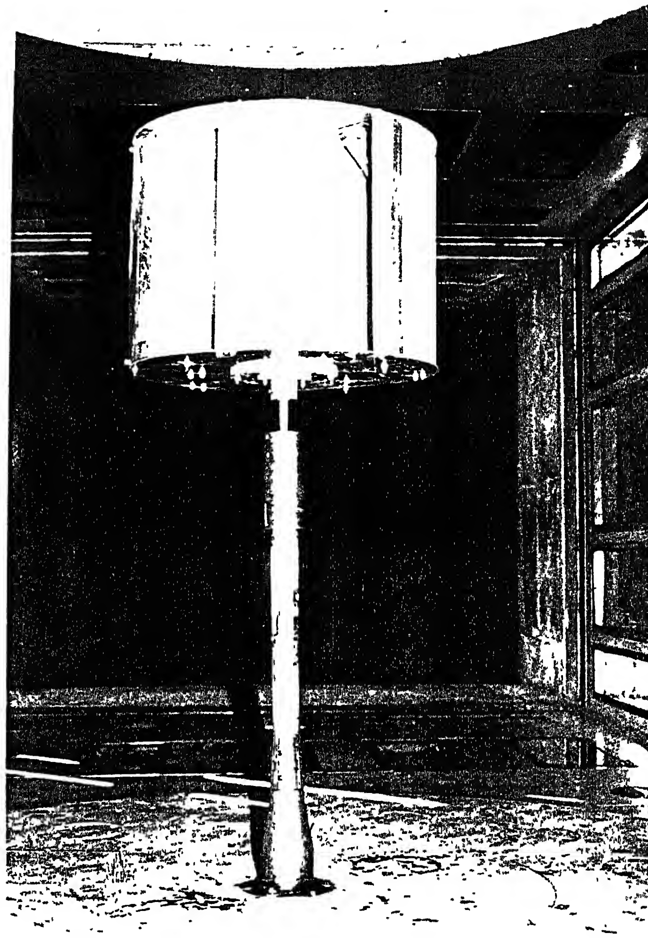

Fig. 4.5 Upstream view of model -